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INTERACTION OF POLLUTION ABATEMENT WITH WORLD DYNAMICS

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16. Abstract

The world dynamics model of Jay W. Forrester is modified to account for pollution abatement. In the modified model, it is assumed that as pollution increases, efforts are made to control pollution. There is a competition between food supply, material standard of living, and pollution abatement for capital, and time is required for diversion of capital toward pollution abatement.

Inclusion of pollution abatement in the model drastically alters the response of the world system for the case in which depletion of natural resources is not considered. Instead of undergoing a pollution catastrophe, all system levels move more or less smoothly toward an equilibrium.

A FORTRAN program listing of the modified world dynamics model is included.

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INTERACTION OF POLLUTION ABATEMENT WITH WORLD DYNAMICS

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SUMMARY

Studies of the world system have been made by Jay W. Forrester and by Donella H. Meadows and associates in which interactions of the world's population, industry, agriculture, natural resources, and pollution were considered. The results of both studies indicated that due to a depletion of natural resources, there will be a decline of the world system. With increased natural resources, these studies indicated that increasing pollution will cause a cataclysm. These results were obtained because the limits to growth of pollution were not included.

This paper presents a modification of the world dynamics model which accounts for pollution abatement and the results obtained from this modified model. This model assumes that as pollution increases, efforts which are measured by capital invested for pollution abatement are made to control pollution. There is a competition between food supply, material standard of living, and pollution abatement for capital, and time is required for diversion of capital to pollution abatement.

Time histories have been computed with the world dynamics model of Forrester modified by the addition of a pollution abatement sector. Inclusion of pollution abatement in the model drastically alters the response of the world system. Instead of undergoing a pollution catastrophe, all system levels move more or less smoothly toward an equilibrium.

A FORTRAN program listing of the world dynamics model modified to include pollution abatement is included.

INTRODUCTION

In recent years, studies of the world as a system of various interrelated and interacting factors have been undertaken. Jay W. Forrester (ref. 1) modeled the world by using system dynamics methods, which have been emerging as powerful techniques for studying complex social systems. This world model has a system composed of five components: population, industry, agriculture, natural resources, and pollution. These five components are governed by a set of five coupled nonlinear differential equations. Obviously, the reduction of the world to five differential equations is a considerable simplification; nevertheless, the world model is a starting point and provides new information on trends and complex interactions. This work was extended by Donella H. Meadows and associates (ref. 2). These modeling techniques have been criticized, but due to lack of viable alternatives, development of models along these lines is currently ongoing. It must be recognized that this type of analysis is presently in its embryonic stage. Computer models of the world will require several years of development before they may be regarded as reliable descriptions of world processes and interactions.

The results of the world studies of both references 1 and 2 indicate that due to depletion of natural resources, there will be a decline of the world system. Population, capital investment, and material standard of living all decrease. Strong arguments can be made that natural resources limitations can be alleviated to some degree by substitution, recycling, and other processes, or that the natural resources were underestimated. A second case was thus considered with reduced usage rate of natural resources or doubled initial natural resources. For this case, a pollution crisis is predicted by the models of both references 1 and 2. Both references present arguments to show that the trend toward a pollution crisis currently exists, for example, as indicated by the DDT and mercury levels in the environment.

The results of using the world dynamics model of reference 1 with natural resources held constant throughout the computer run are shown in figure 1. The case with constant natural resources is the "most optimistic" case. It is seen from the figure that population and capital investment[1] increase, with pollution increasing exponentially. Due to its influence on birth and death rates and on argiculture, the pollution causes a catastrophe with a precipitous drop in population. After the decline of population and industry, pollution is gradually absorbed by the environment and a recovery of the world system begins.

The system response just discussed assumes that no effective efforts are taken to control pollution. It also provides another warning of the consequences of ignoring pollution. However, people will not simply watch such a degradation of the environment without taking action. Already the use of DDT is being banned in some of the more developed countries and international accords have been reached on dumping of toxic metal in the ocean. In addition, efforts are under way to improve air quality in industrial areas. The results of figure 1 were obtained because there were no limits to the growth of pollution in the model.

The purpose of this paper is to present a modification of Forrester's world dynamics model which accounts for pollution abatement and to give the results obtained with this

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[1] The capital unit is defined in reference 1 as the total capital investment per person in 1970. Similarly, the pollution unit is defined as the amount of pollution per person in 1970.

modified model. The modified model assumes that as pollution increases, efforts are made to reduce the generation of pollution. At present, such efforts are not free but require the diversion of capital. As such, pollution abatement must compete with material standard of living and food supply for capital. The present model is simply one of the many steps which will be required in the evolution of world dynamics models. It must be recognized that as yet such studies are speculative.

A study entitled "Interaction of Population Growth, Industrial Growth and Pollution Control" (ref. 3) has many similarities to the present analysis. In that study, population is assumed to grow exponentially with time, and the pollution generation multiplier due to capital is assumed to increase linearly with time. The pollution generation rate multiplier due to pollution abatement is assumed to decrease exponentially with time to a constant value. Thus, the rate of generation of pollution is modeled in reference 3 as a given explicit function of time. The present paper relates pollution abatement to other factors of the model through feedback loops and includes, for example, competition with other components of the model for capital funds.

One characteristic of a computer model involving socioeconomic factors is the explicit and quantitative statement of interrelations between various factors. Usually, this quantitative information is not available. In order to study the world system, numbers were assumed where necessary for these relationships. This lack of hard data for the various relationships is the basis for much of the criticism of the work discussed in references 1 and 2. This need for information indicates research areas. The present study shares this weakness of lacking hard data.

The approach taken herein is to make studies of the world system response for various quantitative assumptions of the pollution abatement interactions. Until data become available, such parametric studies can provide useful information and can guide the efforts to obtain such information.

Another criticism of the work of references 1 and 2 is that the models are too agglomerated. There is a single number for each of the five system levels, without regard for distribution. For example, there is only one number for pollution regardless of type – whether it be DDT, mercury, nitrogen oxides in air, or others – and regardless of how it is distributed geographically. This weakness of the models is due simply to their early stage of development and, again, is shared by the present study.

Computations were carried out with the Control Data series 6000 computer systems using a FORTRAN language program which is listed in an appendix. This program was adapted from the DYNAMO language program of reference 1.

COMPUTER PROGRAM NOTATION

BRPM	birth rate multiplier due to pollution
CFIP	CIPF required by QLP
CI	capital investment
CIAF	CI fraction for agriculture
CIAFN	"normal" (or nominal) CIAF
CIPF	CI fraction for pollution abatement
CIPFTM	response time for CIPF
CIQR	factor to account for competition between material standard of living and food supply
CQFP	factor to account for competition between pollution abatement and food supply
CQMP	factor to account for competition between pollution abatement and material standard of living
CIR	capital investment ratio, CI/P
DRPM	death rate multiplier due to pollution
ECIR	effective capital investment ratio
FPM	food multiplier due to pollution
FR	food ratio
MSL	material standard of living
NR	natural resources
NREM	natural resources extraction multiplier

NRMM	natural resources multiplier due to material
P	population
PLGRIM	pollution generation rate reduction due to CIPF multiplier
POL	pollution
POLCM	pollution generation multiplier due to capital
POLG	pollution generation rate
POLN	number for normalizing pollution
QL	quality of life
QLC	QL factor due to crowding
QLF	QL factor due to food supply
QLM	QL factor due to material standard of living
QLP	QL factor due to pollution

MODELING OF POLLUTION ABATEMENT IN WORLD DYNAMICS

The approach taken in this paper is to modify Jay Forrester's world dynamics model by adding a pollution control sector. Nomenclature in this paper is the same as that of reference 1, with additional terms introduced as defined herein. In this section, the dynamics of pollution abatement and its interactions with the other sectors of the world model are discussed, and a model incorporating these effects is defined.

People, with their various activities, create pollution. As the population P increases and the activities as measured by capital investment CI increase, the amount of pollution POL increases. (See fig. 1.) The pollution POL causes a decrease in quality of life QL, as expressed by the quality of life multiplier due to pollution QLP.

As people sense the deterioration of the environment and quality of life, a social pressure is generated to counter this threat and to reduce pollution. Already efforts are under way to curb pollution. These efforts include improved treatment of sewage, precipitators on industrial chimneys, banning of soft coal, development of insecticides to replace DDT, and controls on industrial emission of toxic metals such as mercury. In a crisis situation, a factory or refinery may be forced to shut down.

In this paper, it is assumed that pollution abatement requires capital. Therefore, the extent of pollution abatement efforts is measured by the fraction of capital investment for pollution abatement CIPF. This fraction of capital investment CIPF represents the expenditure of funds, for example, for precipitators on chimney stacks and sewage treatment plants, and requires a diversion of funds from other activities. The economic loss due to a factory forced to shut down because of its emissions is part of the CIPF.

Because capital is diverted for pollution abatement, the material standard of living is directly affected. There is a trade-off between quality of life due to material standard of living and quality of life due to pollution. In the present paper, this effect is accounted for by defining the effective capital investment ratio ECIR as

$$\mathrm{ECIR} = \mathrm{CIR} \times \mathrm{NREM} \times (1 - \mathrm{CIAF} - \mathrm{CIPF})/(1 - \mathrm{CIAFN})$$

This definition is the same as that used in reference 1 except for the inclusion of the term CIPF. In this equation, CIR is the capital investment ratio, defined by $\mathrm{CIR} = \mathrm{CI}/\mathrm{P}$. The natural resources extraction multiplier NREM is taken to be 1 inasmuch as the natural resources are not assumed to be depleted. CIAF is the fraction of capital investment devoted to agriculture, and CIAFN is the "normal" CIAF value which was taken to be 0.3.

It is assumed that pollution abatement is brought about by the sensing of the decline of quality of life due to pollution QLP. As this decline occurs, it is recognized that an increase in capital investment for pollution abatement CIPF is demanded. As QLP declines, the demanded CIPF increases. The demanded CIPF as indicated by QLP alone is denoted by CFIP. Thus, CIPF is the existing fraction of capital investment for pollution abatement, and CFIP is the level demanded due to QLP. CFIP is not the fraction of capital investment which will eliminate pollution but is the amount which people are willing to divert. As will be seen, it is assumed that pollution cannot be eliminated, only reduced. CFIP is assumed to vary with QLP, as shown in figure 2. The solid-line curve in the figure represents the assumed basic or "normal" case and the dashed-line curve represents the case for which CFIP has twice the "normal" CFIP for a given QLP. For $\mathrm{QLP} = 1$, that is, no noticeable pollution, there is no pressure for pollution abatement. As QLP declines, CFIP increases gradually until pollution reaches alarming proportions and then increases faster. In the present paper, it is assumed that $\mathrm{CFIP} = 1$ for $\mathrm{QLP} = 0$ which may be interpreted to mean that when pollution is intolerable, all effort is diverted to pollution abatement.

There is a competition between food supply, material standard of living, and pollution abatement for capital. People who are underfed are less able to divert efforts toward pollution abatement than are well fed people. Also, people living in poverty are less able to divert efforts toward pollution abatement than are people whose material standard of living is high. These effects are accounted for in the same manner as was done in reference 1 for the balance between quality of life due to material and due to food, where the multiplier CIQR was introduced. The competition of material standard of living with pollution abatement is accounted for by a multiplier CQMP which is a function of the ratio QLM/QLP, where QLM is the quality of life factor due to material standard of living. The function assumed in this paper is shown in figure 3. For the assumed "normal" (1970) condition, QLM/QLP = 1 and CQMP = 1. As the quality of life due to material standard of living improves relative to that due to pollution, the amount of effort to be diverted to pollution abatement is assumed to increase, as expressed by the increase of the multiplier CQMP. Conversely, as the quality of life due to material decreases, the CIPF to be diverted decreases but is not allowed to vanish. The competition between food requirement and pollution abatement is handled in like manner. A multiplier CQFP is defined as a function of the ratio QLF/QLP, where QLF is the quality of life multiplier due to food. This function is shown in figure 4. Its variation is similar to that of CQMP, except for leveling off at large QLF/QLP values. The effect of CQFP is to give food supply precedence over pollution abatement. The demanded fraction of capital investment diverted for pollution abatement modified to account for food and standard of living requirements is defined as CFIP × CQMP × CQFP.

The diversion of capital investment for pollution abatement is by no means immediate, but is a slow process. There is a time required for the problem to be recognized, for social pressure to be generated, for solutions to be found, and for laws to be enacted and put into effect. The CIPF is thus assumed to be governed by the following first-order differential equation:

$$\frac{dCIPF}{dT} = (CFIP \times CQMP \times CQFP - CIPF)/CIPFTM$$

where T is time and CIPFTM is the response or characteristic time for CIPF. It is assumed in writing this equation that the response time for pollution abatement action is the same as the replacement time for equipment as represented by CIPF, but this assumption is not necessary.

The effects of efforts to reduce pollution are now considered. Such efforts are almost always aimed at reducing the rate of generation of pollution POLG rather than cleaning up existing pollution; that is, the recovery of a major body of water from a highly polluted condition is left to natural processes after the pollution source has been reduced.

The effect of capital investment for pollution abatement is modeled by multiplying the pollution generation rate POLG by a factor PLGRIM, which is a reduction of pollution generation rate due to CIPF. A plot of this factor is shown in figure 5. If there is no pollution abatement, that is, CIPF = 0, then PLGRIM = 1. It is assumed that a small CIPF brings about a large reduction in PLGRIM. As CIPF increases, the amount of reduction of pollution generation for a given increase in CIPF decreases. It becomes increasingly difficult to reduce further the effluents of industry and sewage. A law of diminishing returns manifests itself. Three curves are shown in figure 5. The solid-line curve represents the "basic" case, which is used unless specifically stated otherwise. The dash-line curve represents the CIPF effectiveness doubled; that is, a given PLGRIM can be attained with only one-half of the required CIPF of the basic case. The long/short-dash-line curve represents the CIPF effectiveness halved. With this multiplier PLGRIM, the pollution generation rate POLG becomes

$$\mathrm{POLG} = \mathrm{P} \times \mathrm{POLN} \times \mathrm{POLCM} \times \mathrm{PLGRIM}$$

where POLN is "normal" pollution generation rate per person and POLCM is the pollution generation multiplier due to capital.

The world dynamics model as modified to account for pollution abatement may be represented in simplified form as shown in figure 6. The additions due to pollution abatement are shown as heavy lines. The natural resources sector, which was suppressed in the present study by holding natural resources NR constant, is indicated by dotted lines. The pollution abatement sector and its interactions with the other sectors of the world dynamics model are shown in figure 7.

The modifications for the pollution abatement sector are assumptions about how the world system would respond to high pollution levels. The required curves, shown in figures 2 to 5, are also arbitrary assumptions and are expected to remain so for years. Pollution abatement is too recent in terms of world dynamics for there to be a broad base of data available on the capital diverted for abatement purposes and its dependence on food supply and material standard of living.

RESULTS AND DISCUSSION OF WORLD DYNAMICS RESPONSE WITH POLLUTION ABATEMENT INCLUDED

Time histories have been computed for the world model with the pollution abatement sector added. All computations started at A.D. 1900. For the basic case, that is, CIPFTM, the response time for CIPF is assumed to be 30 years. The resulting time histories of the system levels for the basic case are shown in figure 8. It is seen that the population P increases to approximately 6 billion people by the year 2050, with a slight oscillation about this value. The pollution level POL increases exponentially until about 2020, after which it oscillates. Capital investment CI increases exponentially until 1980, after which its growth rate becomes constant until 2050. Long-term computations show that CI levels off at 22 billion capital units. Agriculture CIAF increases to approximately 0.4. Pollution abatement CIPF increases until about 2040, and after a brief decline it again increases. Long-term computations show that for this model CIPF levels off at 0.22, oscillating slightly about this value.

Quality of life QL and quality of life multipliers due to crowding QLC, due to pollution QLP, and due to material standard of living QLM are shown in figure 9 from 1900 to 2100. Quality of life QL does not change substantially, varying between 0.8 and 1.2 over the two centuries presented. The quality of life multiplier due to crowding QLC declines over most of the time interval; the computed long-term limit is 0.68. The quality of life multiplier due to pollution QLP declines to 0.75. These effects are countered by the quality of life multiplier due to material standard of living QLM that increases linearly until 2030, after which it slowly increases to a limit of 2.0.

The effect of response time for pollution abatement CIPFTM is studied next. Cases were run in which the response times were taken to be 15 and 45 years, in addition to the basic case of 30 years. The population P for each of the three cases is shown in figure 10. The results are indistinguishable for all three response times until after the year 2000. For CIPFTM = 15 years, the population overshoots slightly and settles down to an equilibrium at 6 billion people. For CIPFTM = 45 years, the population oscillates. For CIPFTM very large (so that effort is never diverted to pollution control), this model reduces to the model of reference 1. It is interesting that even with CIPFTM = 45 years, the cataclysmic results of figure 1 are avoided.

The pollution levels for these three response times are shown in figure 11. The results for CIPFTM = 15 years are fairly smooth. For CIPFTM = 45 years, the pollution has a rather large oscillation, although the peaks are not nearly as severe as in figure 1. The capital investment CI is not shown but is found to be the same for all three response times until 2070, the three curves separating slightly in the closing decades of the 21st century.

The fraction of capital investment for pollution abatement CIPF is shown in figure 12 for the same three response times of figures 10 and 11. For no CIPFTM is there any CIPF until 1985,[2] after which all three CIPFTM curves move upward. For CIPFTM = 15 years, CIPF increases steadily; for CIPFTM = 45 years, an oscillation

[2] The significance of 1985 is found in figure 9. It is seen that in 1985, QLP drops below 1.0 for the first time; this causes a demand for pollution abatement.

is present. For all three response times, CIPF goes to a limit of 0.22. (Recall that the response time of a system does not affect the equilibrium state, but only the transient in arriving at the state.)

As a point of curiosity, it was found that for CIPFTM less than 32 years, the long-term behavior of the system is damped to a steady state. For CIPFTM greater than the critical response time of 32 years, the system oscillates in a limit cycle.

The question of effectiveness of capital investment diverted for pollution abatement CIPF is now considered for the three cases of figure 5 – namely, the basic case and the cases with CIPF more effective and less effective than the basic case. The resulting behavior of the world model for these three cases is shown in figures 13 to 18. Figure 13 shows that with increased effectiveness of pollution abatement, pollution is significantly reduced, especially where the basic case has overshoots. With reduced effectiveness of pollution abatement, pollution has larger oscillations. The effects of pollution on birth and death rates cause corresponding effects on population. The effect of CIPF effectiveness on capital investment CI is shown in figure 14. This influence comes about primarily through the population. Figure 15 shows CIAF and CIPF. It is seen that the fraction for agriculture increases due to more effective CIPF because there are more people who are better fed and because there is less capital required for pollution abatement. The quality of life multiplier due to pollution QLP is shown in figure 16. Most of the time, QLP is higher for the more effective CIPF; however, during an oscillation, the QLP for the less effective CIPF actually exceeded the QLP for the more effective CIPF for a brief time. The quality of life multiplier due to crowding QLC is shown in figure 17. Because of the suppressive effect of pollution on population, increased effectiveness of CIPF results in increased population, with a resulting decline in QLC. Finally, the overall quality of life QL is shown in figure 18. Curiously, most of the time, quality of life QL is reduced because of more effective pollution abatement. This effect is mainly due to increased population which in turn results in decreased quality of life due to crowding QLC, even though quality of life due to pollution QLP has improved. Overall, the effects of doubling the effectiveness of pollution abatement were rather disappointing in terms of quality of life, according to the present model. It is noted that quality of life is intangible and very much subject to opinion. However, a single figure of merit is useful in these comparisons, provided that its limitations are kept in mind.

What is the effect of being more critical of pollution than was originally assumed? If people are more critical of pollution, they will increase the fraction of capital expended for pollution abatement. In order to study this effect, the CFIP for a given QLP is doubled, and this condition is shown by the dash-line curve in figure 2. The resulting world behavior is shown in figure 19. Except for CIPF, the results are almost the same as those of figure 13, where CIPF was assumed to be twice as effective. The CIPF is considerably higher in figure 19. The reason for the results being so similar is simply that although a factor of 2 appears in different places, resulting PLGRIM is the same in both cases.

From the cases presented herein, it appears that overall results of the model are not very sensitive to the precise numerical details of the pollution abatement sector. Pollution overshoots may be worsened or ameliorated by slow or rapid abatement responses, and these overshoots may be reduced by stronger abatement. The cataclysmic results obtained without pollution abatement were avoided. The world model with pollution abatement considered approaches its limits to growth fairly smoothly. Capital investment and material standard of living increase smoothly, with growth leveling off toward the end of the 21st century. Numerical studies with the model bring out the rather obvious fact that there will be as much pollution as people will allow.

Three assumptions inherent in this study should be emphasized. First, it was assumed that pollution abatement requires the expenditure of effort. The economic costs due to the presence of pollution, such as man-hours lost and medical expenses due to illnesses aggravated by pollution, are not considered in the world dynamics model except in the food production. Pollution abatement reduces the economic costs of pollution, and these costs should be deducted from the costs of pollution abatement. Thus, it is quite possible for pollution abatement to show a profit in direct overall economic costs. These considerations do not even include quality of life considerations. This fact was not included in the present study. Second, it was assumed that the methods available for pollution abatement are constant with time. Pollution abatement costs may be expected to decrease with time, as technology develops and methods improve. Third, it was assumed that depletion of natural resources will not be critical in the world system. As modeled in references 1 and 2, depletion of natural resources causes a collapse of the world system. It may be argued that scarcity of one resource leads to the development of substitutes, and many examples may be cited to support this view. This argument is the basis of the assumption of constant natural resources. The process of developing substitutes for depleted resources is critical and needs study.

A long-term computer run was made with the world model without pollution abatement and with natural resources held constant. This is a rather academic but interesting exercise. The results are shown in figure 20. It is seen that the model is in a limit cycle condition, of which the peak and collapse shown in figure 1 is only the first cycle. It is emphasized that by no stretch of the imagination should this computer run be considered a prediction. Figure 20 is presented only to demonstrate the behavior of the model. It is interesting to speculate that during the Middle Ages in Europe, such cycles of population and plague occurred. It is possible that systems analysis techniques may prove helpful to historians in studying cause and effect interactions in history. This would in turn upgrade the ability to apply these methods to studies of the problems presently facing mankind.

CONCLUDING REMARKS

The world dynamics model of Jay W. Forrester has been modified by including a pollution abatement sector. For constant natural resources, the results of the world dynamics model without pollution abatement include a pollution cataclysm. With pollution abatement included, there is no cataclysm; instead, population and industry fairly smoothly approach their limits to growth. Pollution also increases to the level that will be tolerated. The fraction of capital which is required to keep pollution at this level has little adverse effect on material standard of living. The effects of various parameters of the pollution abatement sector were studied and it was found that the results of the modified model were changed only slightly.

This study brings out the point that although pollution is a problem, based on the assumptions made in this study, it can be brought under control and need not cause a collapse of the world system.

It is recommended that models be constructed of the world system by using the approach of reference 1 modified to consider the world as several interacting major geographic areas. In this manner the primary objection of the world model, that is, overaggregation, could be reduced and additional relationships examined.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., August 20, 1973.

APPENDIX

PROGRAM LISTING FOR WORLD DYNAMICS MODEL WITH POLLUTION ABATEMENT INCLUDED

The computer program for the world dynamics model modified to include the pollution abatement sector is listed in this appendix in FORTRAN IV language. A field length of 55 000 octal locations is required. Time required for a 200-year case is approximately 7 seconds for the central processing unit (CPU) and 9 seconds for the peripheral processing unit (PPU).

```
      PROGRAM WORLD    (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C        JAY FORRESTER≠S WORLD DYNAMICS MODEL
C          INCLUDE CAPITAL INVESTMENT FOR POLLUTION CONTROL
C              5/5/72
      DIMENSION BRMMT(10), QLMFT(10), DRMMT(15), DRPMT(10), DRFMT(10),
     ADRCMT(10),BRCMT(10), BRFMT(10),CFIFRT(10), QLMT (10), QLCT (15),
     B QLFT(10), QLPT(10), FRT3(10),  CIQRT(10), BRPMT(10), FCMT (10),
     CFPCIT(10), CIMT(10),  FPMT(10),POLCMT(10),POLATT(10), CIRAT(10),
     D  CRT(10), FRT(10),              POLRT(10), FRT2 (10), CRT2 (15)
     E, CFIPT(10), COMPT(10), QLPT2(10), QMPT(10), CQFPT(10), QFPT(10),
     F CIPFT (15), PLGRIMT(15)
      REAL NRUN, NRFR, NREM, MSL, NR1, LA, NR, NRMM, NRUR, NR1N,
     A NREMT(10), NRMMT(15), MSLT(15), MSLT2(15), NRFRT(10)
      NAMELIST/NAM1/KFPCI, KFCM, KNREM, KBRMM, KFPM,KCIM,KPOLAT,KPOLCM,
     A KBRPMT, KBRFMT, KBRCMT, KDRCMT, KDRFMT, KDRPMT, KDRMMT, KNRMMT,
     B KQLPT , KQLFT , KQLCT , KQLMT , KCIQRT, KCFIFR, NPRINT,
     C TIME1,  TIMEN , DT,CI1, CIAF1 , CIAFT , P1,NR1, LA,PDN, POLS,
     D POL1 ,  BRMMT , NREMT , DRMMT , DRPMT , DRFMT , DRCMT , BRCMT,
     E BRFMT,  BRPMT , FCMT  , FPCIT , CIMT  , FPMT  , POLCMT, POLATT,
     FCFIFRT,  QLMT  , QLCT  , QLFT  , QLPT  , NRMMT , CIQRT , CIRAT,
     G CRT  ,  NRFRT , MSLT  , POLRT , FRT   , FRT2  , MSLT2 , CRT2 ,
     H QLMFT,  FRT3 ,NRUN,POLN,NR1N
     I, CIPF1, CIPFT, KQLP2, KQMP, KQFP, KPLGR, CFIPT, COMPT, QLPT2,
     J  QMPT, CQFPT, CIPFT, PLGRIMT ,QFPT ,CIPFTM
C         PRELIMINARY
      READ(5,NAM1)
      P=P1 $ NR=NR1 $ CIAF=CIAF1 $ TIME=TIME1 $ CI=CI1 $ POL=POL1
      CIPF= CIPF1
      BRN=.04 $ ECIRN=1. $          DRN=.028 $ QLS=1. $ FC=1. $ FN=1.
      CIAFN=.3 $ CIGN=.05 $ CIDN=.025
      N=0
      WRITE (6,NAM1)
      WRITE (6,90)
      WRITE (6,93)
      WRITE (6,91) TIME,P,NR,CI,CIAF,POL, QL,MSL,FR,BR,DR
      WRITE (6,92) CIPF,CFIP, CQMP, CQFP
    2 DO 1 I=1,NPRINT
C         COMPUTE DEPENDENT CONDITIONS
      CR= P/(LA*PDN)
      CIR=CI/P
      CIRA=CIR*CIAF/CIAFN
      NRFR=NR/NR1N
      CALL FTLUP (NRFR,NREM, 1,KNREM,NRFRT,NREMT)
      ECIR=CIR*(1.-CIAF-CIPF)*NREM/(1.-CIAFN)
      MSL= ECIR/ECIRN
```

APPENDIX

```
      CALL FTLUP (CIRA,FPCI, 1,KFPCI,CIRAT,FPCIT)
      CALL FTLUP (CR   ,FCM , 1,KFCM ,CRT   ,FCMT )
      POLR=POL/POLS
      CALL FTLUP (POLR,FPM , 1,KFPM ,POLRT,FPMT)
      FR= FPCI*FCM*FPM*FC/FN
C          COMPUTE BIRTH RATE
      CALL FTLUP (CR   ,BRCM ,1,KBRCMT,CRT   ,BRCMT )
      CALL FTLUP (FR   ,BRFM ,1,KBRFMT,FRT   ,BRFMT )
      CALL FTLUP (MSL,BRMM,   1,KBRMM,MSLT ,BRMMT)
      CALL FTLUP (POLR,BRPM ,1,KBRPMT,POLRT,BRPMT )
      BRR=  BRMM*BRPM*BRFM*BRCM*BRN
      BR=BRR*P
C          COMPUTE DEATH RATE
      CALL FTLUP (CR   ,DRCM ,1,KDRCMT,CRT   ,DRCMT )
      CALL FTLUP (FR   ,DRFM ,1,KDRFMT,FRT2 ,DRFMT )
      CALL FTLUP (MSL ,DRMM ,1,KDRMMT,MSLT2,DRMMT )
      CALL FTLUP (POLR,DRPM ,1,KDRPMT,POLRT,DRPMT )
      DRR=  DRMM*DRPM*DRFM*DRCM*DRN
      DR=DRR*P
C          COMPUTE CAPITAL RATES
      CALL FTLUP (MSL ,CIM , 1,KCIM ,MSLT, CIMT )
      CIG= P*CIM*CIGN
      CID= CI*CIDN
C          COMPUTE AGRICULTURAL FRACTION RATES
      CALL FTLUP (FR   ,QLF   ,1,KQLFT ,FRT   ,QLFT   )
      CALL FTLUP (MSL ,QLM   ,1,KQLMT ,MSLT ,QLMT   )
      QLMF = QLM/QLF
      CALL FTLUP (QLMF,CIQR ,1,KCIQRT,QLMFT,CIQRT )
      CALL FTLUP (FR   ,CFIFR,1,KCFIFR,FRT3 ,CFIFRT)
C          COMPUTE NATURAL RESOURCE USAGE RATE
      CALL FTLUP (MSL ,NRMM ,1,KNRMMT,MSLT ,NRMMT )
      NRUR= P*NRMM*NRUN
C          COMPUTE POLLUTION RATES
      CALL FTLUP (POLR,POLAT,1,KPOLAT,POLRT,POLATT)
      CALL FTLUP (CIR ,POLCM,1,KPOLCM,CIRAT,POLCMT)
      POLA= POL/POLAT
      POLG= P*POLN*POLCM
      CALL FTLUP (CIPF, PLGRIM,1,KPLGR, CIPFT,PLGRIMT)
      POLG = POLG*PLGRIM
C          COMPUTE CAPITAL FOR POLLUTION CONTROL
      CALL FTLUP (POLR,QLP   ,1,KQLPT ,POLRT,QLPT   )
      CALL FTLUP (QLP,CFIP ,1,KQLP2,QLPT2,CFIPT)
      QMP= QLM/QLP
      CALL FTLUP (QMP,CQMP,1,KQMP,QMPT,CQMPT)
      QFP= QLF/QLP
      CALL FTLUP (QFP,CQFP,1,KQFP,QFPT,CQFPT)
      DCIPF = CFIP*CQMP*CQFP-CIPF
C          INTEGRATE GDE FOR SYSTEM LEVELS
      P=P+DT*(BR-DR)
```

```
      CI=CI+DT*(CIG-CID)
      CIAF=CIAF+(CFIFR*CIQR-CIAF)*DT/CIAFT
      NR=NR+DT*(-NRUR)
      POL=POL+DT*(POLG-POLA)
      TIME=TIME+DT
      CIPF  =CIPF+DCIPF*DT/CIPFTM
    1 CONTINUE
C
      CALL FTLUP (CR   ,QLC   ,1,KQLCT ,CRT2 ,QLCT  )
      QL= QLS*QLM*QLC*QLF*QLP
      IF (CIPF.LT.1.E-5) CIPF=0.
C          OUTPUT
      WRITE (6,91) TIME,P,NR,CI,CIAF,POL, QL,MSL,FR,BR,DR
      WRITE (6,92) QLC,QLF,QLM,QLP ,CIG,CID,POLG,POLA,POLAT,NRUR
      WRITE (6,92) BRR,DRR,POLR,NRFR,CR,CIRA,CIR,QLMF,CFIFR,CIQR
      WRITE (6,92) CIPF,CFIP, CQMP, CQFP ,PLGRIM
      IF (TIME.LT.TIMEN) GO TO 2
      STOP
C
   90 FORMAT (//5X*TIME  POPULATION  NAT RESOUR  CAP INVEST  CI AGRIC FR
     A  POLLUTION  QUAL LIFE  MAT STAN LIV FOOD RATIO  BIRTH RATE  DEATH
     B RATE* /13X*QL CROWD    QL FOOD     QL MATER    QL POLLUT    CI GE
     CN    CI DISCAR  POLL GEN    POLL ABSOR  POLL AB TI  NR USE RAT*/
     D11X*BIRTH RATE  DEATH RATE  POLLUT RAT  RESO LEFT   CROWDING    CI
     ER AGRIC  CAP INV RAT QUAL LIF MAT  CFIFR         CIQR*/)
   91 FORMAT(/3XF7.1,10E12.4)
   92 FORMAT (10X,10E12.4)
   93 FORMAT (10X*CI POL CONTR   CFIP* 9X*CQMP* 8X*CQFP*)
      END
 $NAM1 KFPCI=7,KFCM=6,KNREM=5,KBRMM=6,KFPM=7,KCIM=6,
 KPOLAT=7,KPOLCM=6,KBRPMT=7,KBRFMT=5,KBRCMT=6,KDRCMT=6,
 KDRFMT=9,KDRPMT=7,KDRMMT=11,KNRMMT=11,KQLPT=7,KQLFT=5,
 KQLCT=11,KQLMT=6,KCIQRT=5,KCFIFR=5,NPRINT=5,
 NRUN=.25,
 NRUN=0., POLN=.1, TIMEN=2300.,
 TIME1=1970., P1=3.68E9, NR1=7.7649E11, CI1=3.8375E9, CIAF1=.28042,
 NRUN=1.,
 TIME1=1970.,TIMEN=2100.,DT=.2,CI1=.4E9,CIAF1=.2,CIAFT=15.,
 TIME1=1900.,DT=.1,NPRINT=10,
 P1=1.65E9,NR1=900.E9,LA=135.E6,PDN=26.5,POLS=3.6E9,POL1=.2E9,
 POLN=1.,
 NRUN=0.,
 NRIN=.9E12,
 TIMEN=2300.,
 CIPFTM=30.,
 NPRINT=100,
 CIPF1=0.,
 POLS=.29225E10,
 CFIPT(1)=1.,.4,.2,.07,0.,0.,
```

APPENDIX

```
QFPT(1)=0.,.5,1.,1.5,2.,
QLPT2(1)=0.,.25,.5,.75,1.,1.25,
CQMPT(1)=.2,.5,1.,1.5,2.,
QMPT(1)=0.,.5,1.,1.5,2.,
CQFPT(1)=.2,.5,1.,1.3,1.5,
PLGRIMT(1)=1.,.4,.3,.24,.2,.17,.15,.13,.12,.11,.1,
CIPFT(1)=0.,.1,.2,.3,.4,.5,.6,.7,.8,.9,1.,
CIPFT(1)=.0,.2,.4,.6,.8,1.0,1.2,1.4,1.6,1.8,2.0,
KQLP2=6,
KQMP=5,
KQFP=5,
KPLGR=11,
BRMMT(1)=1.2,1.,.85,.75,.7,.7,
NREMT(1)=0,,.15,.5,.85,1.,
DRMMT(1)=3.,1.8,1.,.8,.7,.6,.53,.5,.5,.5,.5,
DRPMT(1)=.92,1.3,2.,3.2,4.8,6.8,9.2,
DREMT(1)=30.,3.,2.,1.4,1.,.7,.6,.5,.5,
DRCMT(1)=.9,1.,1.2,1.5,1.9,3.,
BRCMT(1)=1.05,1.,.9,.7,.6,.55,
BREMT(1)=.0,1.,1.6,1.9,2.,
BRPMT(1)=1.02,.9,.7,.4,.25,.15,.1,
FCMT(1)=.5,1.,1.4,1.7,1.9,2.05,2.2,
FPCIT(1)=.5,1.,1.4,1.7,1.9,2.05,2.2,
CIMT(1)=.1,1.,1.8,2.4,2.8,3.,
FPMT(1)=1.02,.9,.65,.35,.2,.1,.05,
POLCMT(1)=.05,1.,3.,5.4,7.4,8.,
POLATT(1)=.6,2.5,5.,8.,11.5,15.5,20.,
CFIFRT(1)=1.,.6,.3,.15,.1,
QLMT(1)=.2,1.,1.7,2.3,2.7,2.9,
QLCT(1)=2.,1.3,1.,.75,.55,.45,.38,.3,.25,.22,.2,
QLFT(1)=0.,1.,1.8,2.4,2.7,
QLPT(1)=1.04,.85,.6,.3,.15,.05,.02,
NRMMT(1)=.0,1.,1.8,2.4,2.9,3.3,3.6,3.8,3.9,3.95,4.,
CIQRT(1)=.7,.8,1.,1.5,2.,
CIRAT(1)=.0,1.,2.,3.,4.,5.,6.,
CRT(1)=.0,1.,2.,3.,4.,5.,
NRFRT(1)=.0,.25,.5,.75,1.,
MSLT(1)=.0,1.,2.,3.,4.,5.,6.,7.,8.,9.,10.,
POLRT(1)=.0,10.,20.,30.,40.,50.,60.,
FRT(1)=.0,1.,2.,3.,4.,
FRT2(1)=.0,.25,.5,.75,1.,1.25,1.5,1.75,2.,
MSLT2(1)=.0,.5,1.,1.5,2.,2.5,3.,3.5,4.,4.5,5.,
CRT2(1)=.0,.5,1.,1.5,2.,2.5,3.,3.5,4.,4.5,5.,
QLMFT(1)=.0,.5,1.,1.5,2.,
FRT3(1)=.0,.5,1,,1,5,2.,
FCMT(1)=2.4,1.,.6,.4,.3,.2$
```

REFERENCES

1. Forrester, Jay W.: World Dynamics. Wright-Allen Press, Inc., c.1971.

2. Meadows, Donella H.; Meadows, Dennis L.; Randers, Jørgen; and Behrens, William W., III: The Limits to Growth. Universe Books, c.1972.

3. Peterson, Ernest W.: Interaction of Population Growth, Industrial Growth and Pollution Control. J. Air Pollution Control Assoc., vol. 23, no. 1, Jan. 1973, pp. 11-16.

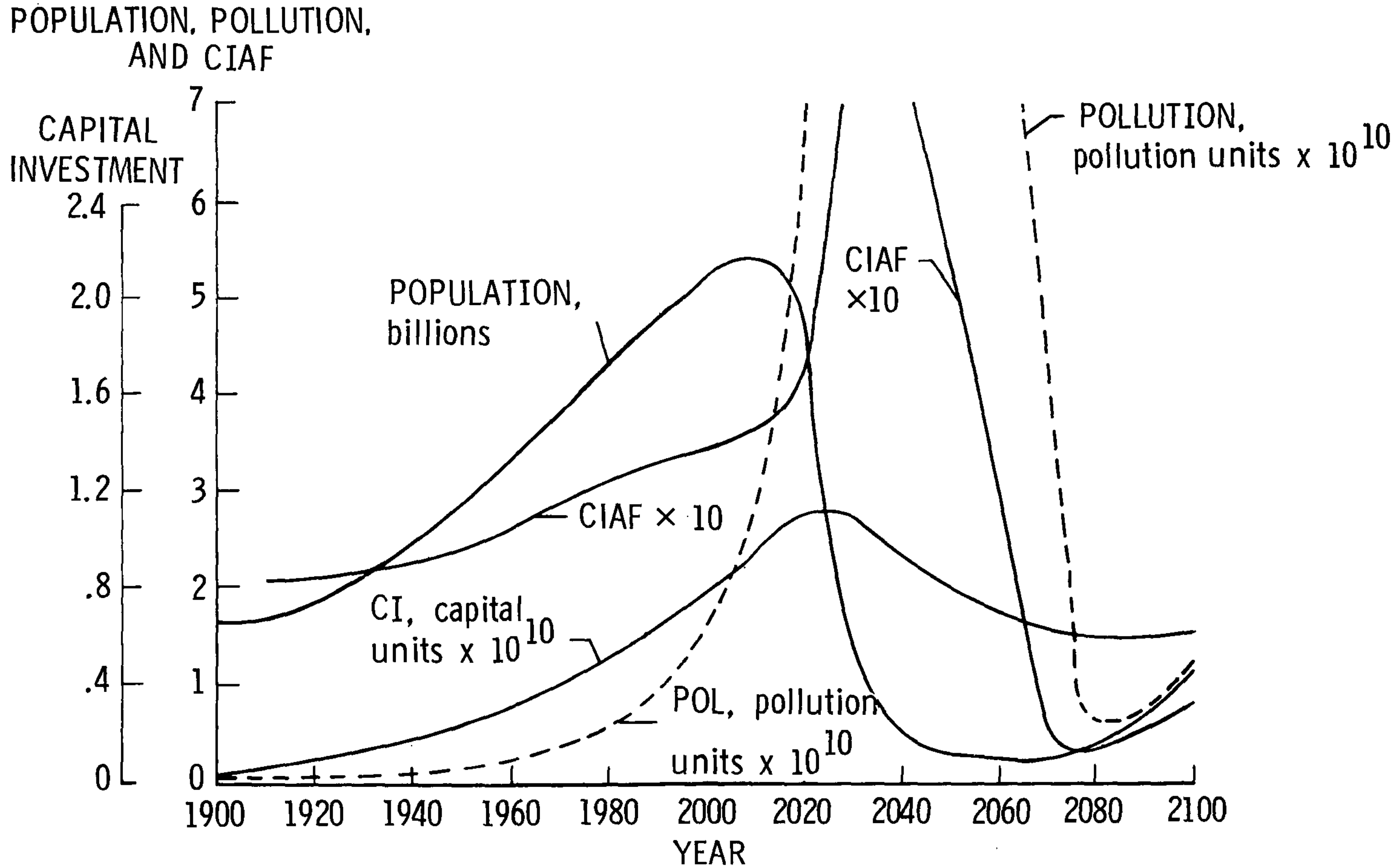

Figure 1.- Behavior of world dynamics model with constant natural resources and no pollution abatement.

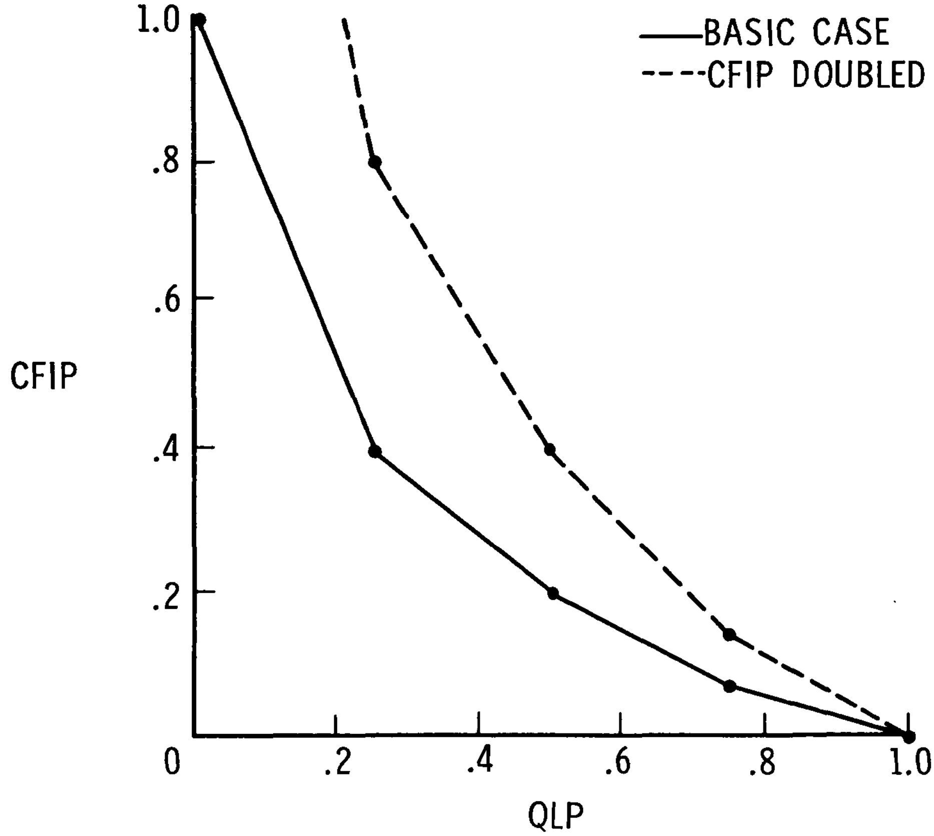

Figure 2.- Fraction of capital investment indicated for pollution abatement as a function of quality of life multiplier due to pollution.

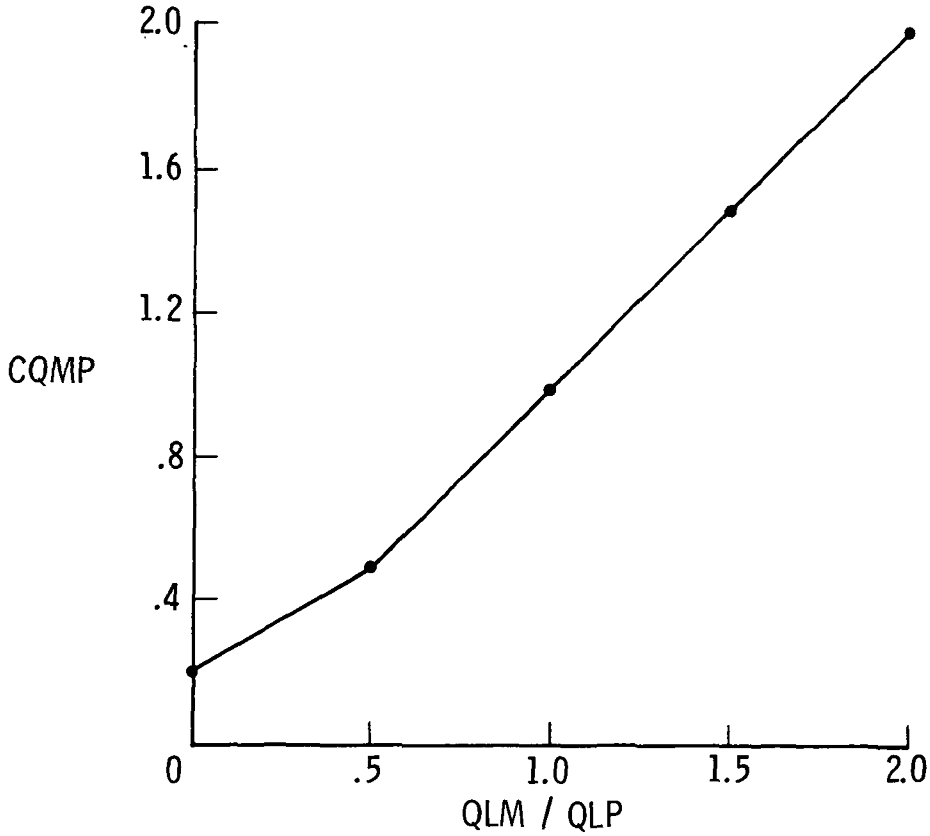

Figure 3.- Pollution abatement multiplier CQMP to account for competition with material standard of living.

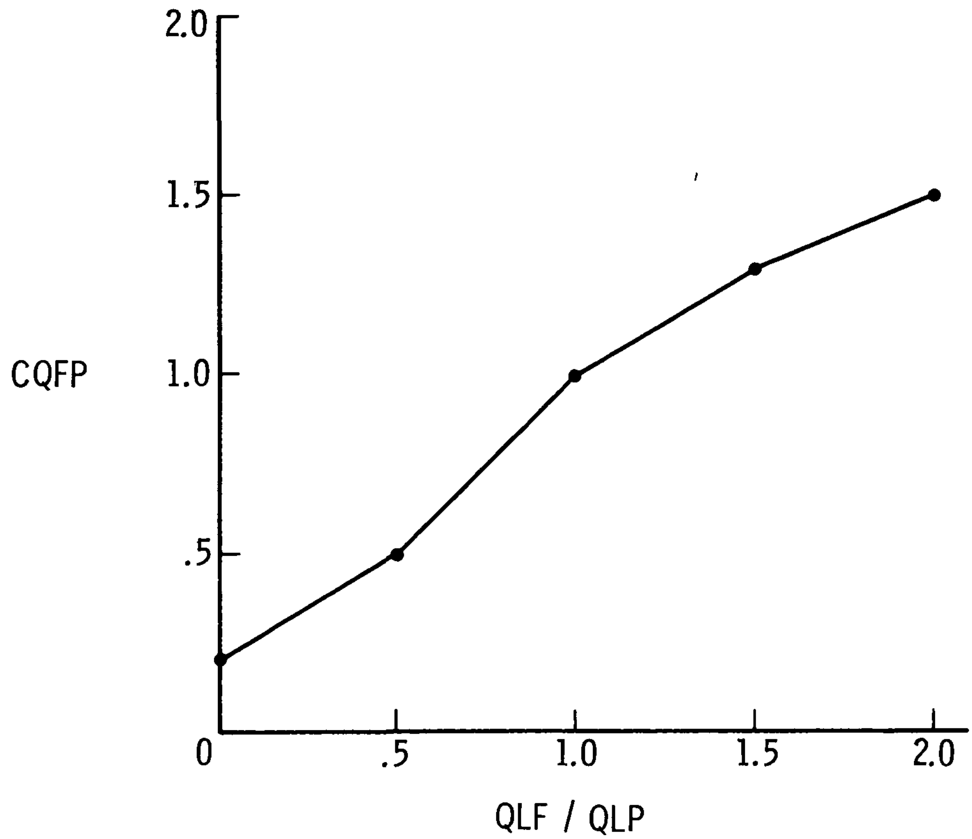

Figure 4.- Pollution abatement multiplier CQFP to account for competition with food supply.

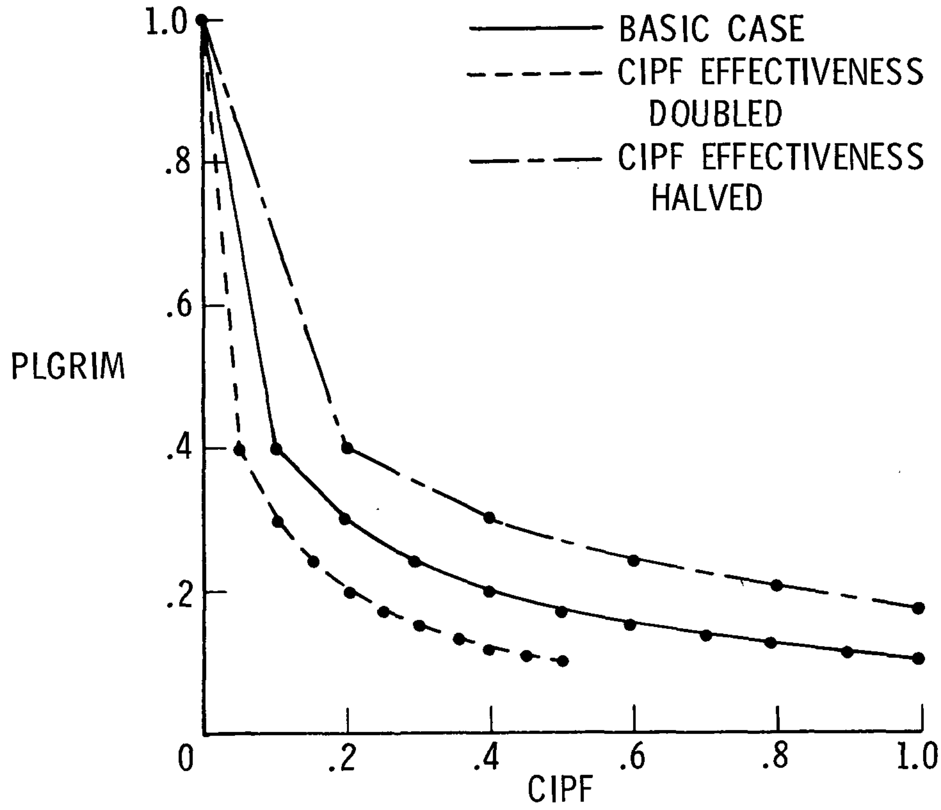

Figure 5.- Pollution generation reduction multiplier as function of capital investment fraction for pollution abatement.

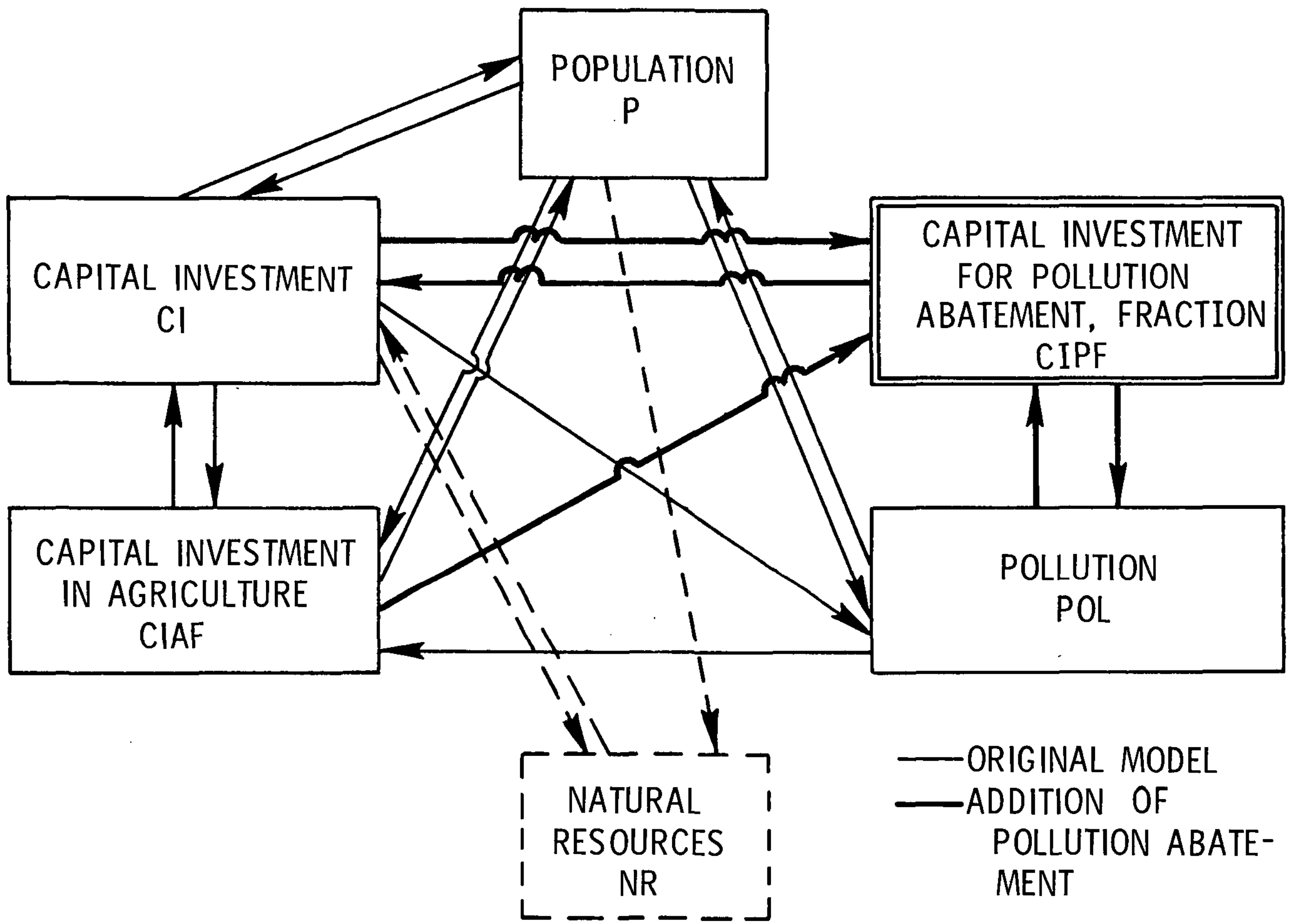

Figure 6.- Interactions of sectors in world dynamics model modified to include pollution abatement.

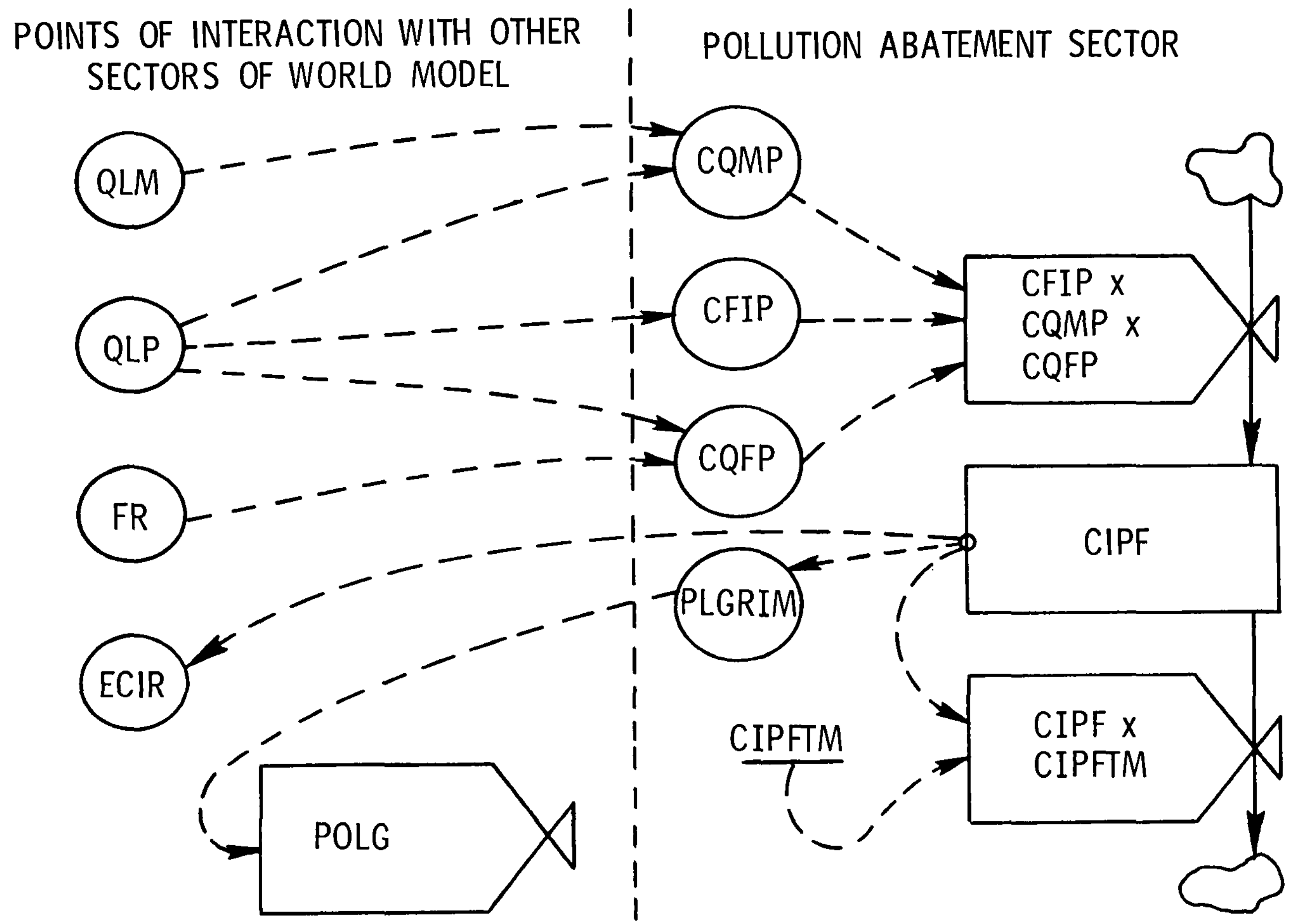

Figure 7.- Diagram of pollution abatement sector and interactions with other sectors of world dynamics model.

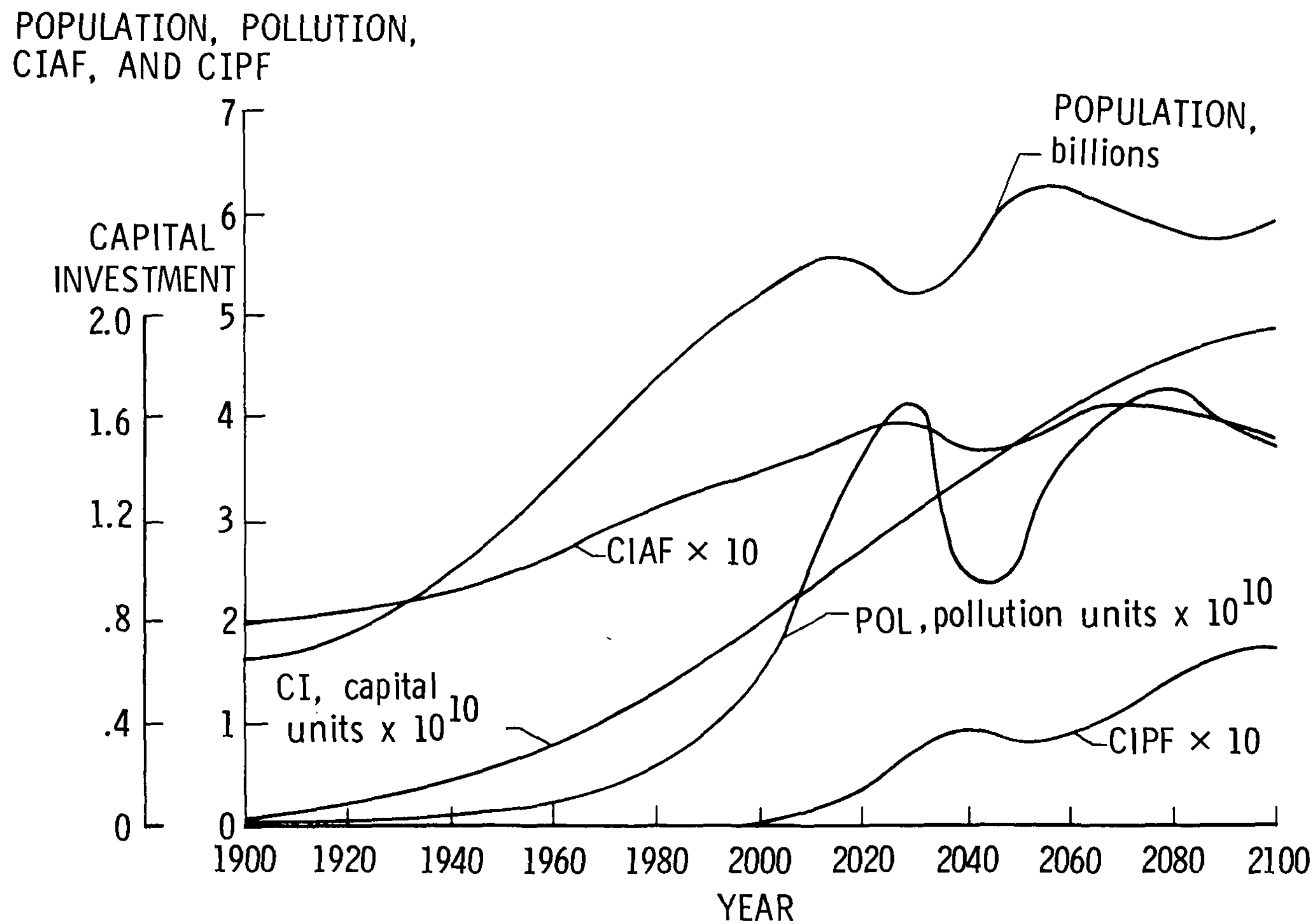

Figure 8.- Behavior of world dynamics model with pollution abatement included. Basic case.

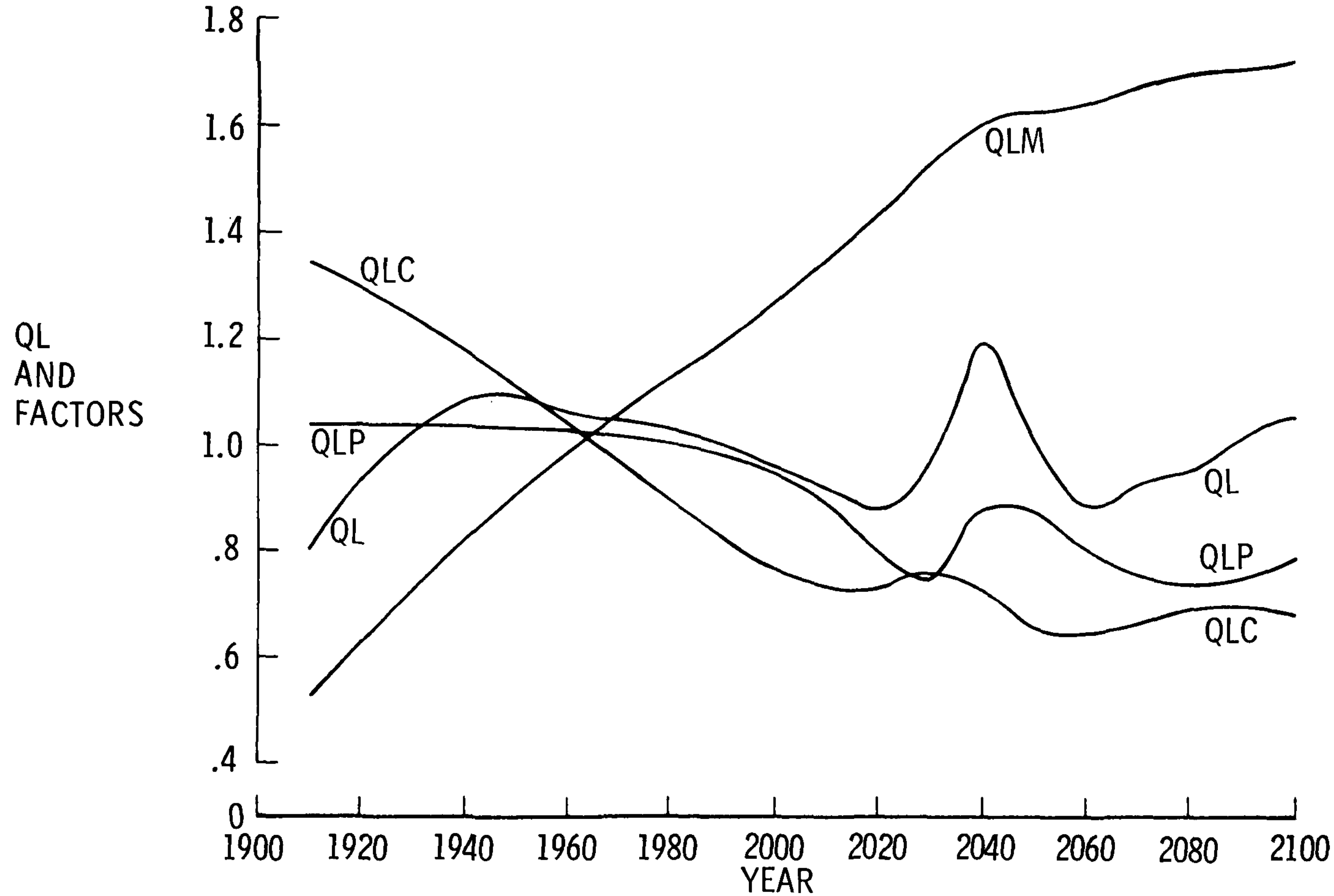

Figure 9.- Quality of life and QL factors with pollution abatement included.

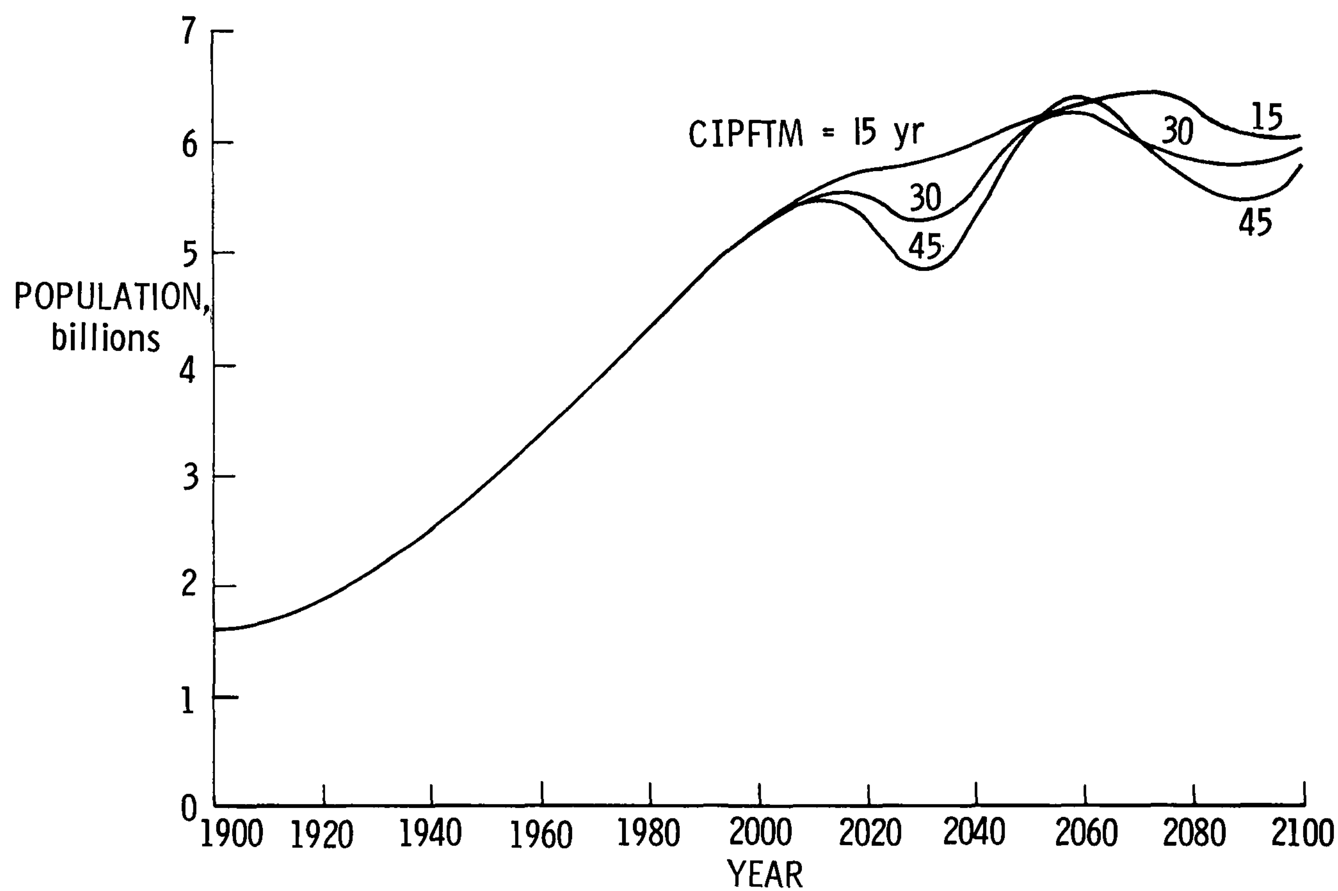

Figure 10.- Effect of pollution abatement response time on population.

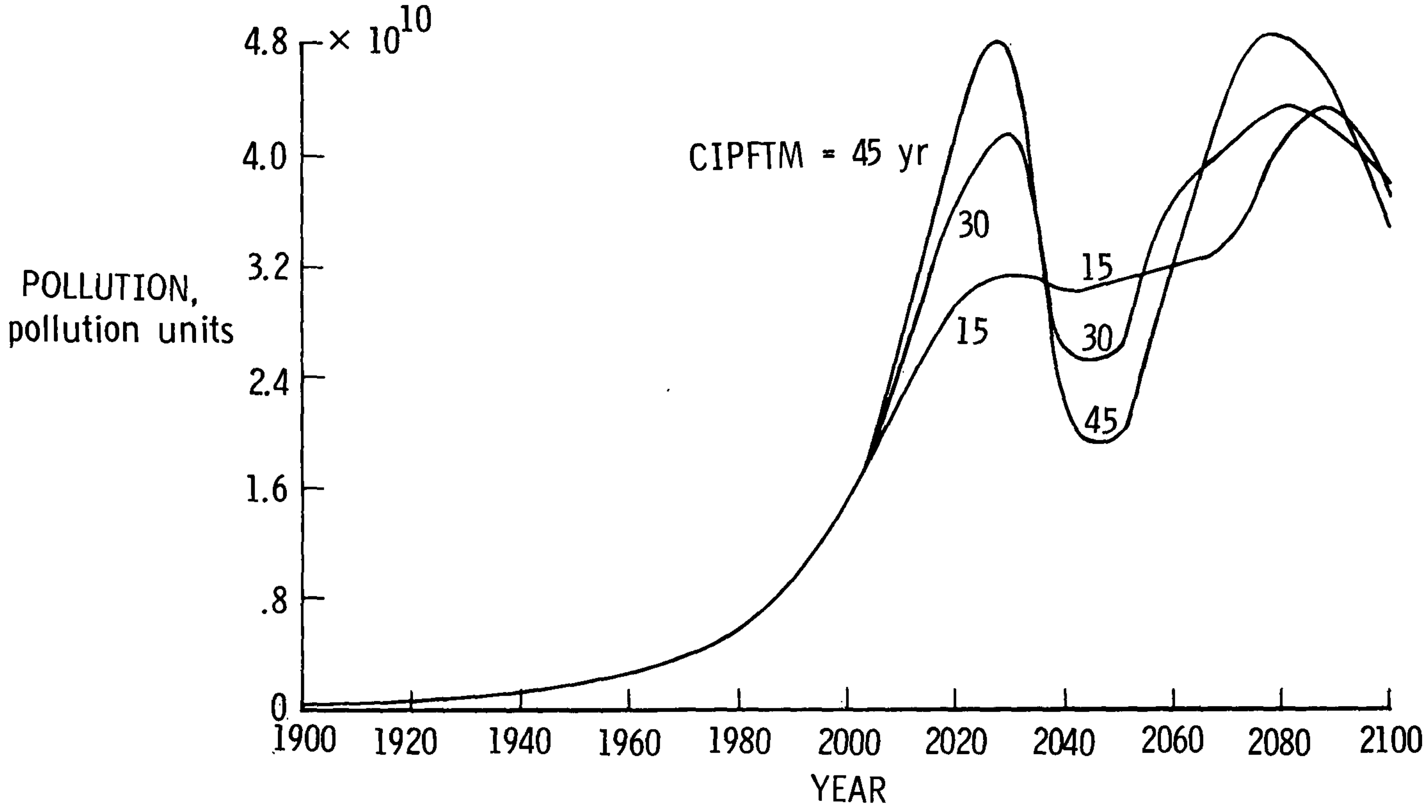

Figure 11.- Effect of pollution abatement response time on pollution.

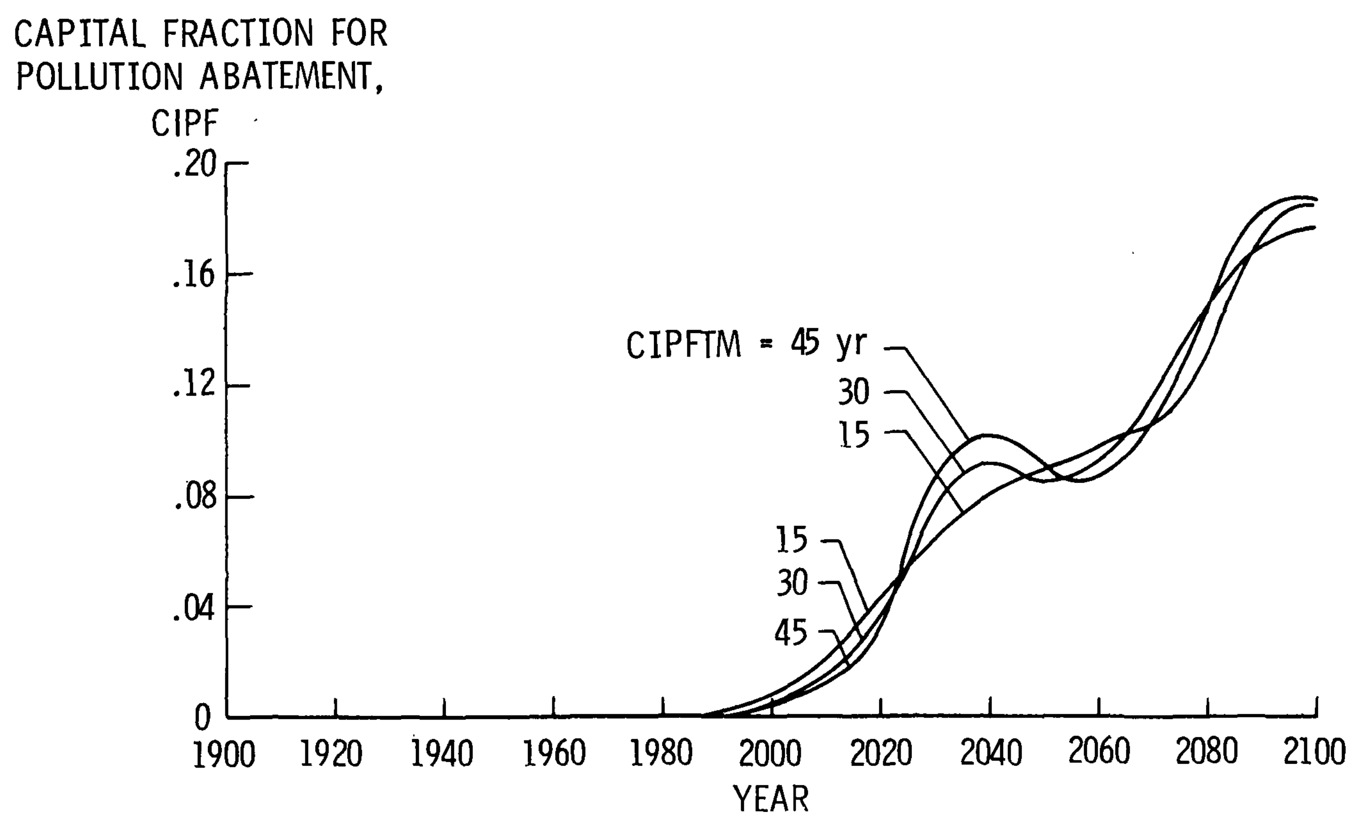

Figure 12.- Effect of pollution abatement response time on capital investment fraction for pollution abatement.

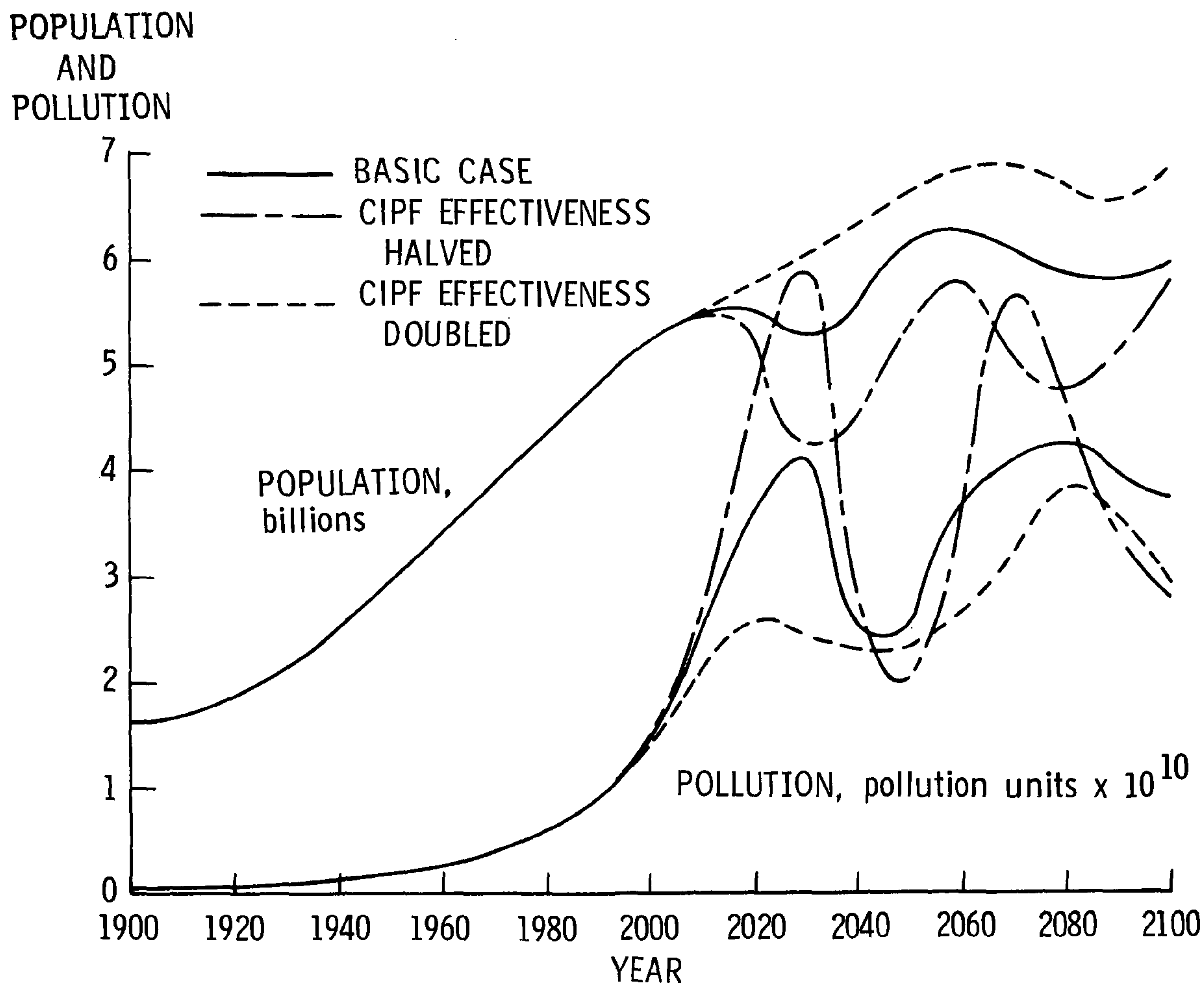

Figure 13.- Effect of CIPF effectiveness on population and pollution.

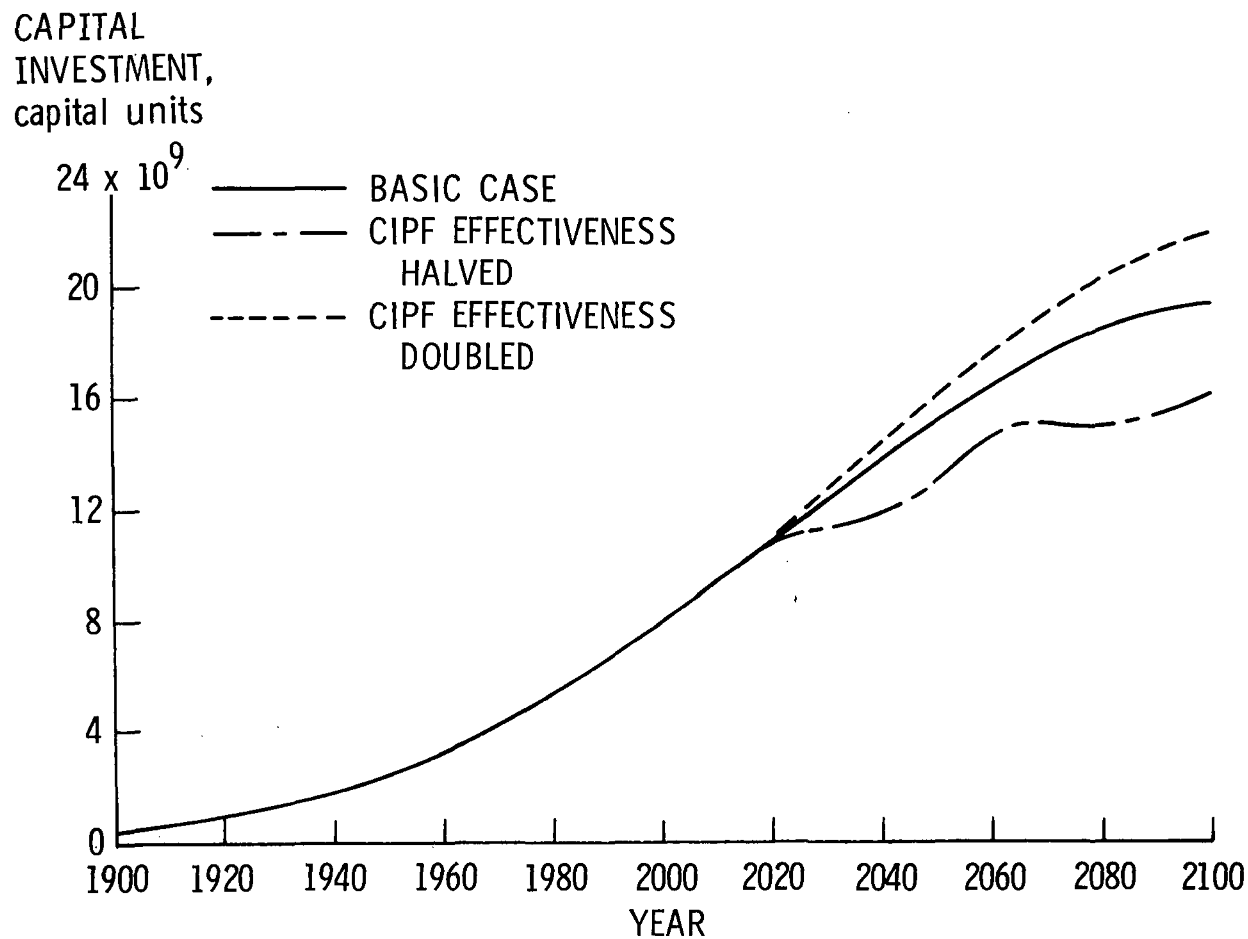

Figure 14.- Effect of CIPF effectiveness on capital investment.

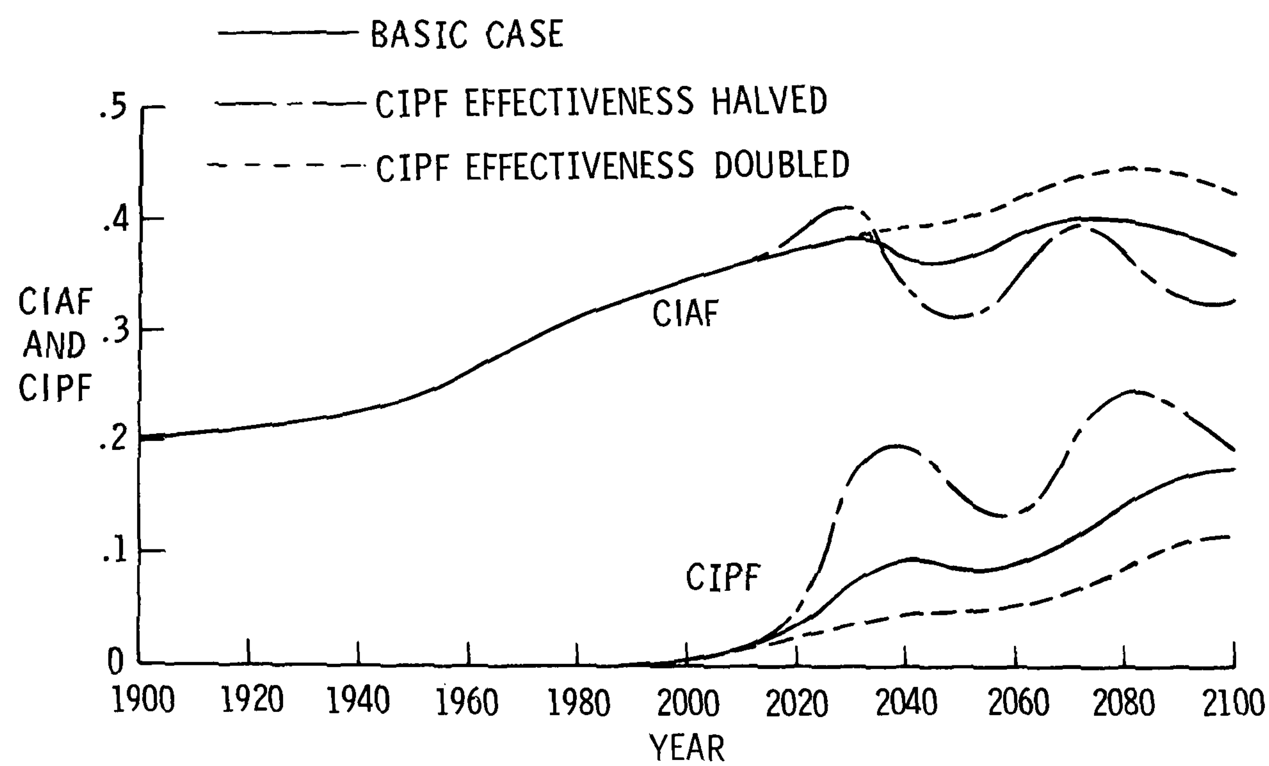

Figure 15.- Effect of pollution abatement effectiveness on capital investment fraction for agriculture and for pollution abatement.

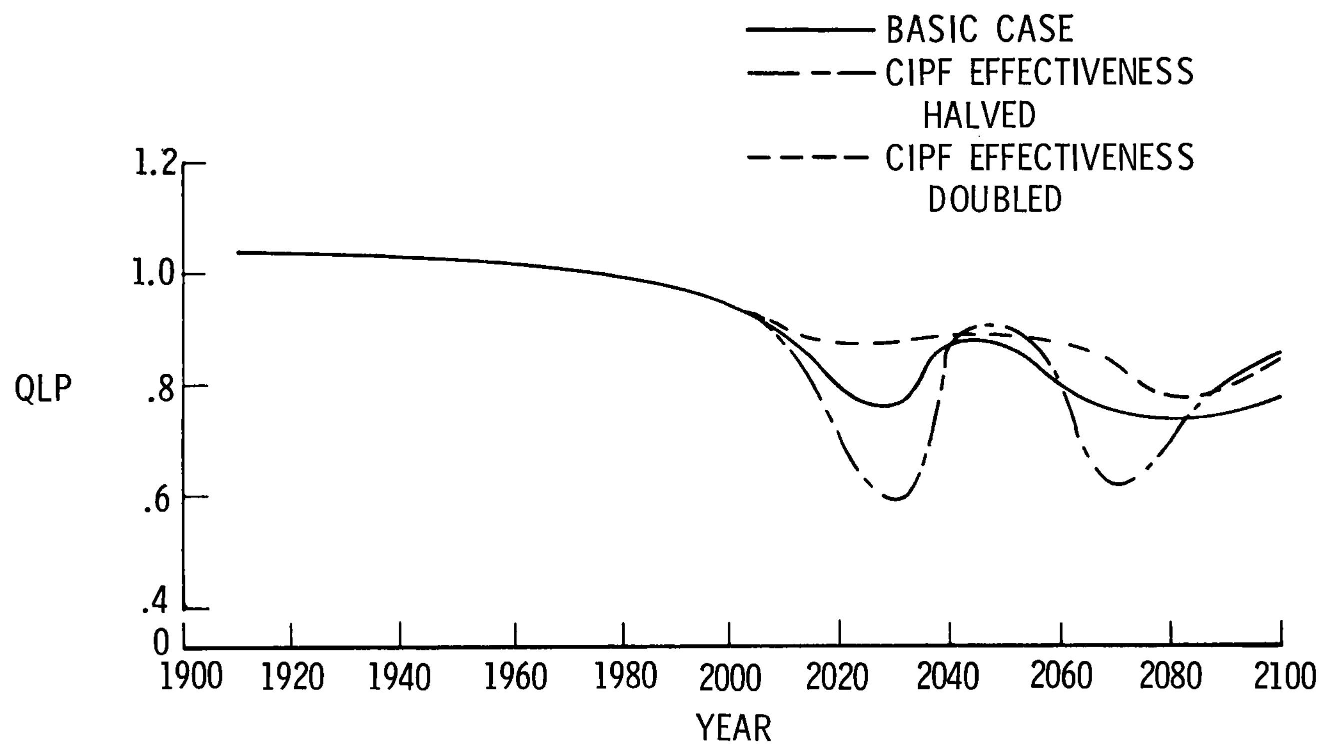

Figure 16.- Effect of CIPF effectiveness on quality of life due to pollution QLP.

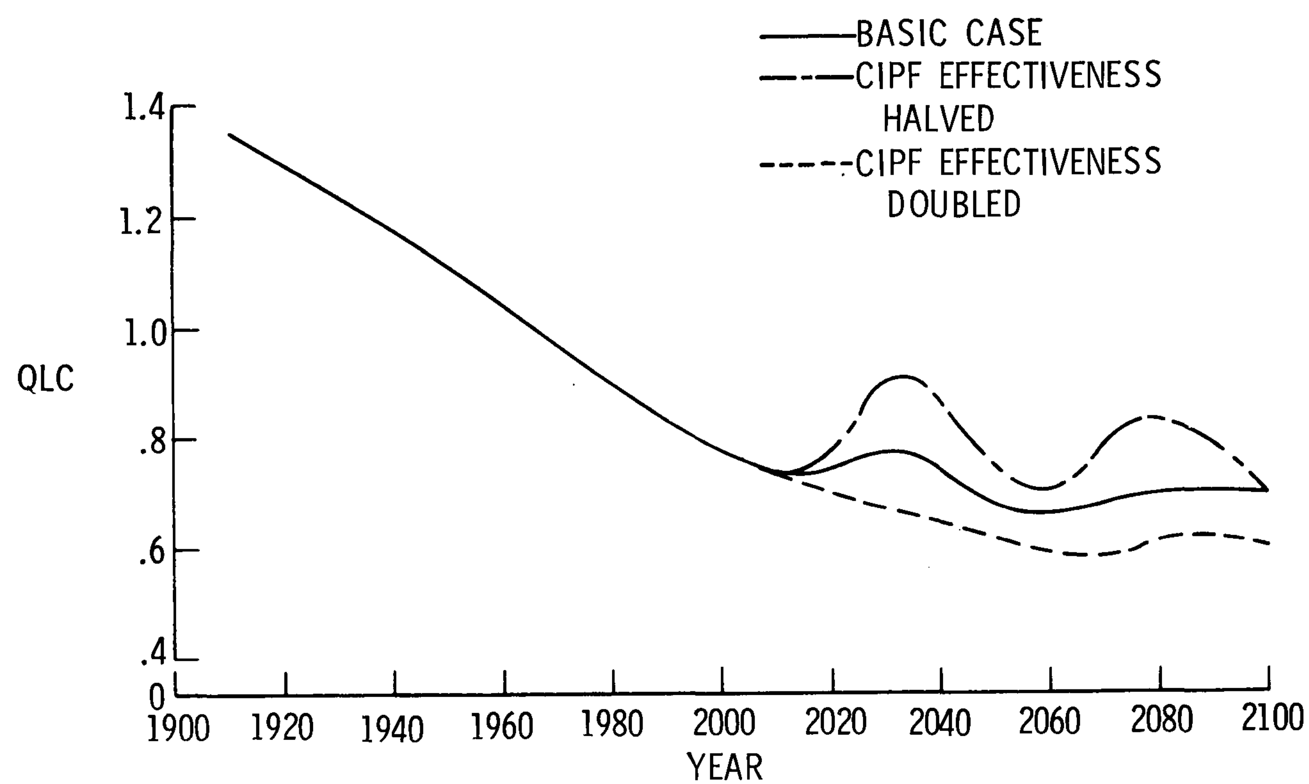

Figure 17.- Effect of CIPF effectiveness on quality of life due to crowding QLC.

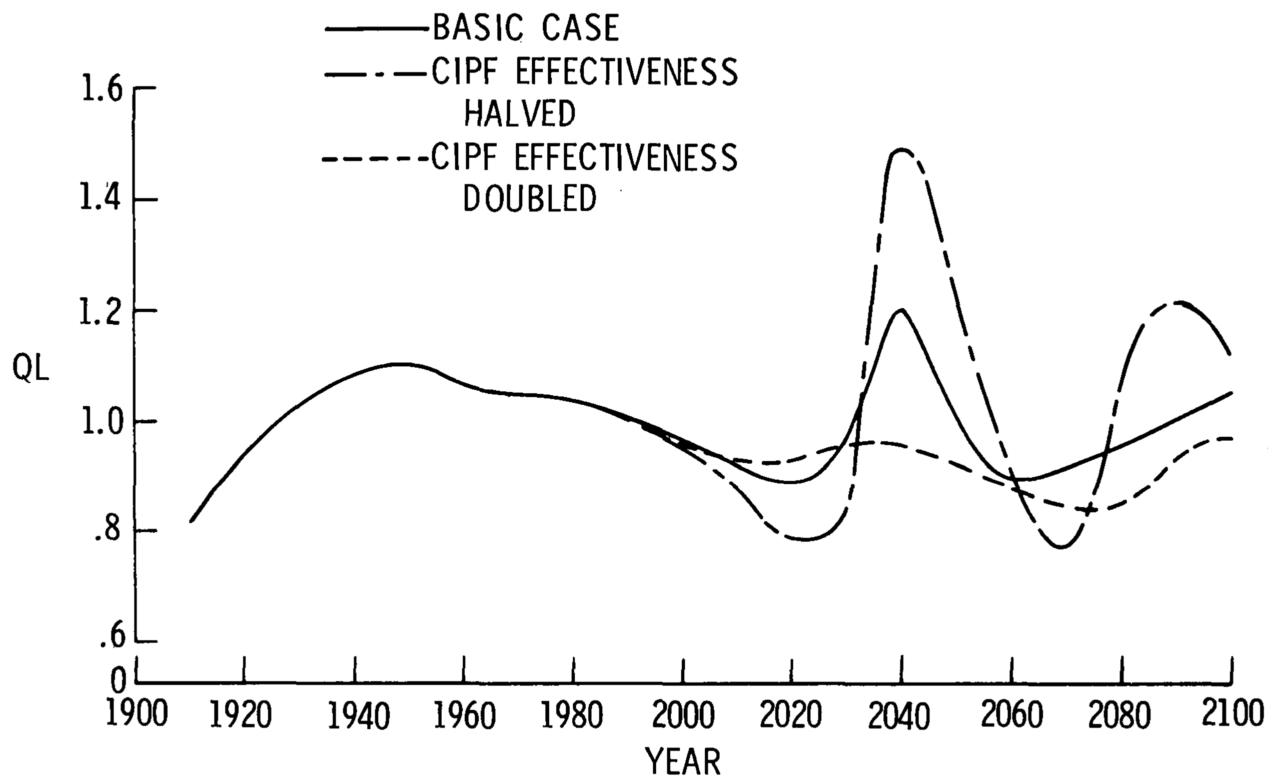

Figure 18.- Effect of CIPF effectiveness on quality of life QL.

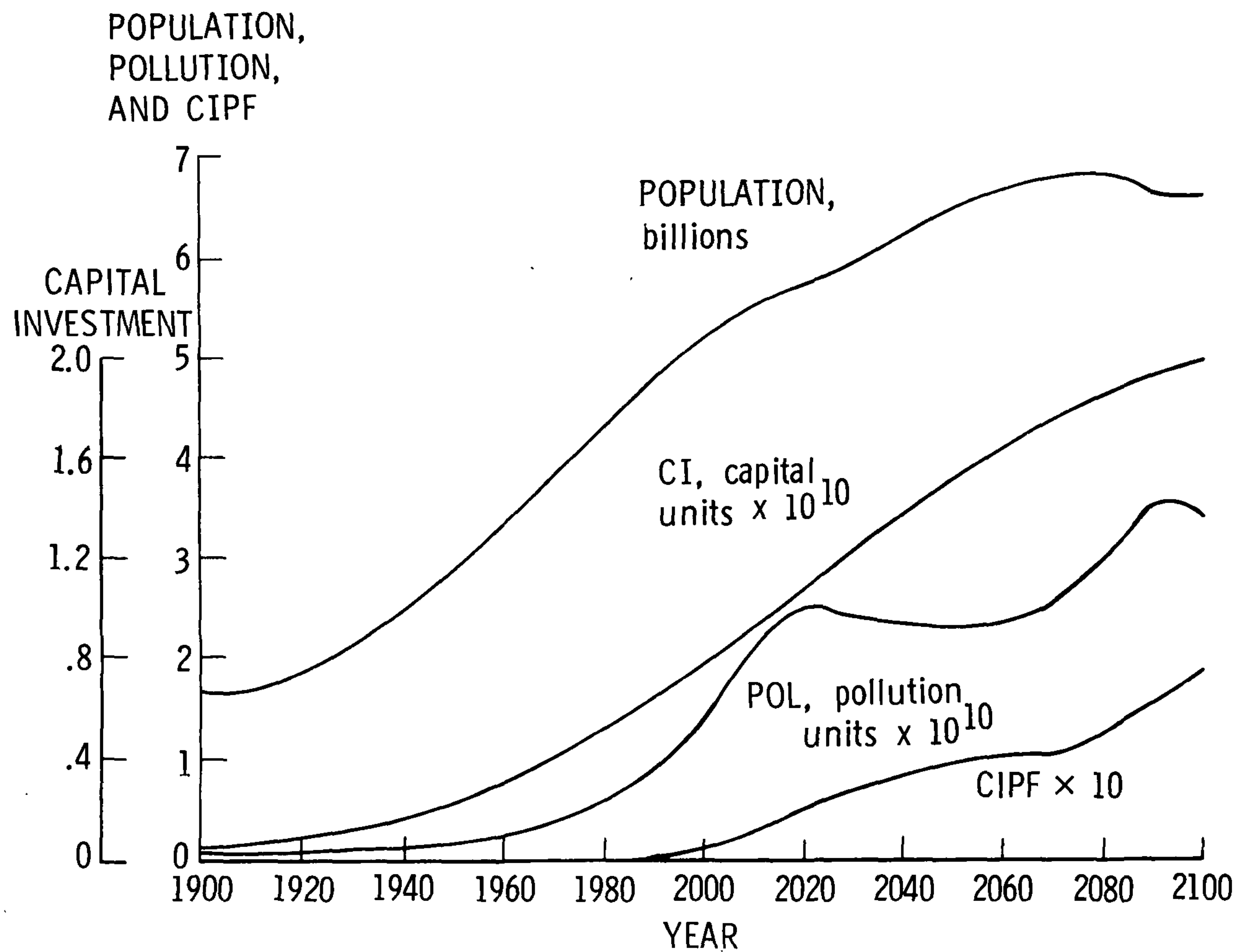

Figure 19.- Behavior of world system model for reduced tolerance of pollution.

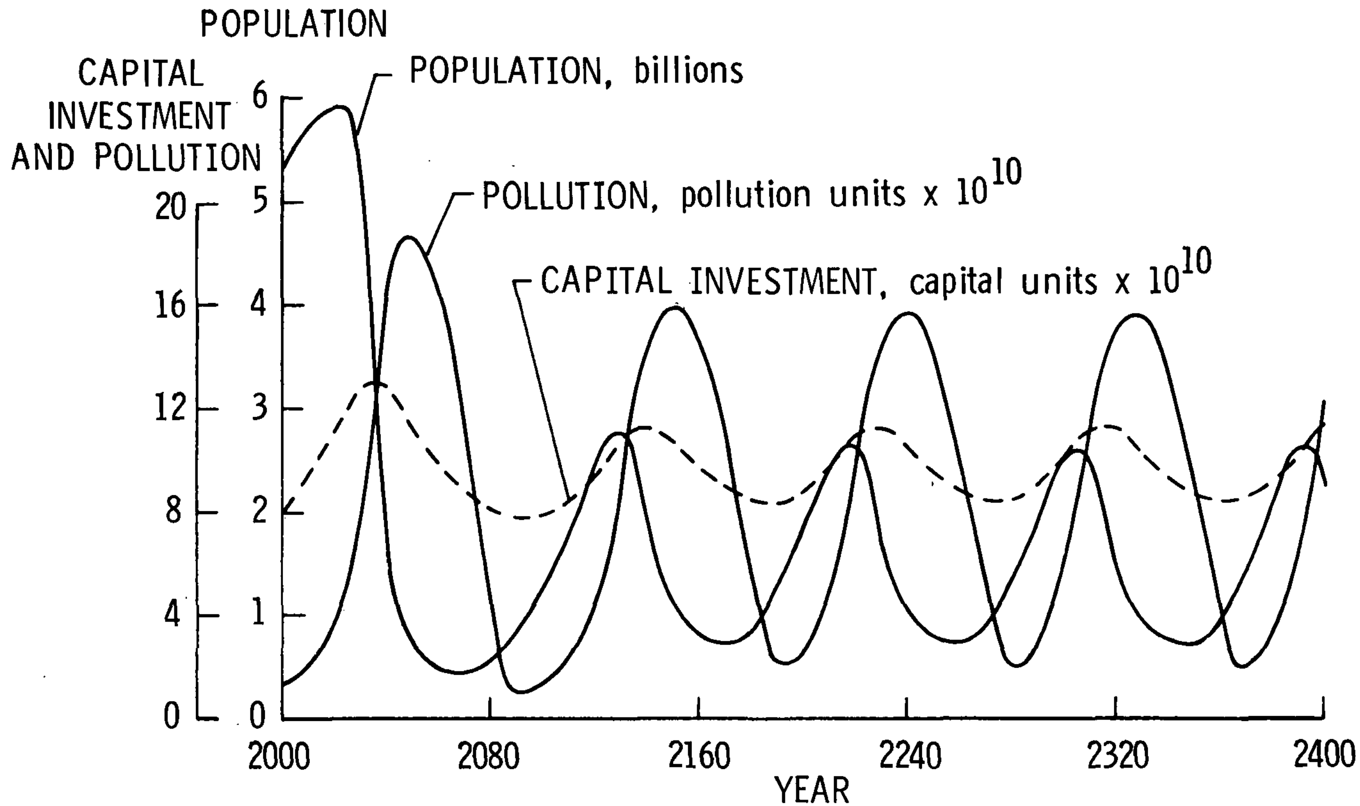

Figure 20.- Limit cycle behavior of world dynamics model with natural resources held constant and no pollution abatement.

NASA-Langley, 1973 —— 34 L-8961

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